Photon-Pair Generation from Chip-Scale Cs Atomic Vapor Cell

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Abstract

The realization of a narrowband photonic quantum source based on a chip-scale atomic device is considered essential in the practical development of photonic quantum information science and technology. In this study, we present the first step toward the development of a photon-pair source based on a microfabricated chip-scale Cs atomic vapor cell. Time-correlated photon pairs from the millimeter-scale Cs vapor cell are emitted via the spontaneous four-wave mixing process of the cascade-type $6S_{1/2}-6P_{3/2}-8S_{1/2}$ transition of ^{133}Cs . The maximum normalized cross-correlation value between the signal and idler photons is measured as 622(8) under a weak pump power of 10 mW. Our photon source violates the Cauchy–Schwartz inequality by a factor of $>10^5$. We believe that our approach has very important applications in the context of realizing practical scalable quantum networks based on atom–photon interactions.

Introduction

Photon sources exploiting atomic media are key components of photonic quantum information technologies based on atom–photon interactions. Such sources can be used to construct quantum information networks consisting of spatially separated nodes to store and process quantum information including quantum repeaters and quantum memory [1–9]. In particular, effective interactions between atomic systems and coherent light are essential for the development of high-quality photon sources based on atomic media [10–17]. Most current experimental setups for photon sources using trapped atoms, such as those based on single atoms, ions, and cold atoms, are complex, bulky, and require high-vacuum conditions; thus, in these setups, it is difficult to manipulate isolated atomic samples [15–19].

Meanwhile, a photon-pair source realized using an alkali atomic vapor cell can afford high device compactness and operational simplicity relative to sources based on cold atomic systems [20–25]. Although warm atomic ensembles are limited by Doppler broadening, this problem of atomic vapor cells has been overcome in the form of a Doppler-free-configuration in a double Λ or cascade type atomic transition. In Cs vapor cell, the twin beam source based on four-wave mixing in a double Λ -scheme has been reported [26]. Recently, bright-photon-pair generation has been experimentally demonstrated using spontaneous four-wave mixing (SFWM) and collective two-photon coherence effects in a cascade-type atomic system [21]. Furthermore, a polarization-entangled photon source from an atomic vapor cell has been experimentally demonstrated using bidirectional counter-propagating pump and coupling lasers [24].

In the atomic-physics community, the chip-scale atomic clock was first fabricated and demonstrated two decades ago using microelectromechanical systems (MEMS) fabrication techniques [27]. Chip-scale atomic devices such as atomic clocks, magnetometers, and gyroscopes continue to open up new possibilities for the development of miniature atom-based instruments [28–32]. In particular, a chip-scale atomic vapor cell combined with silicon waveguides or waveguide optics can potentially be applied in various quantum devices such as single-photon sources and quantum memories based on atomic

ensembles. However, to the best of our knowledge, photon-pair generation from chip-scale atomic vapor cells has not thus been reported.

Here, we experimentally demonstrate the generation of photon pairs via the SFWM process from a chip-scale warm atomic ensemble of ^{133}Cs atoms for the first time. Our chip-scale atomic vapor cell is a simple and small device that is fabricated by the anodic bonding of silicon and glass. Bright photon pairs can be generated from this chip-scale atomic ensemble with weak laser pumping on the order of tens of microwatts. To characterize the generated photon pairs, we measured the cross-correlation between the signal and idler photons. Furthermore, we observed the quantum beats of the temporal biphoton waveform of the photon pair generated via SFWM multi-channels relating to the hyperfine states of the intermediate state of the $6P_{3/2}$.

Experimental Setup

For the Cs vapor cell [Fig. 1(a)] in our setup, borosilicate wafers on both sides of a through-hole-patterned Si wafer are bonded using anodic bonding. The vapor cell outer dimensions are 2 mm · 3.5 mm · 1.4 mm. This setup also includes a cesium metal dispenser without a buffer gas, as shown in Fig. 1(b). After bonding, the Cs dispenser is activated in situ by a high-power laser, and pure Cs atoms move from the dispenser to the photon-pair chamber for photon-pair generation through a channel. The diameter and thickness of the photon-pair chamber were 1.5 mm and 1 mm, respectively.

Here, we note that the collective two-photon coherence effect is important for the generation of bright photon pairs from Doppler-broadened warm atoms [21]. Two-photon resonance occurs via the application of counter-propagating pump and coupling lasers satisfying the Doppler-free two-photon resonant condition in the warm atomic ensemble. In our setup, as shown in Fig. 1(c), the pump and coupling lasers are counter-propagated, focused, and spatially overlapped in the photon-pair chamber.

The pump and coupling lasers are orthogonally linearly polarized along the horizontal (H) and vertical (V) polarization directions, respectively. Owing to the conservation of angular momentum in the SFWM process, the generated photon pair in the two-photon decay is polarization-correlated with the perpendicular linear-polarized signal/idler (H/V or V/H) photons. However, to minimize laser-scattering noise at the single-photon detectors (SPDs, PerkinElmer SPCM-AQRH-13HC), the polarizations of the signal and idler photons are selected as linear polarizations (V/H) orthogonal to those (H/V) of the pump and coupling lasers. The emitted signal and idler photons are counter-propagated in the phase-matched direction and coupled into two single-mode fibers positioned at a tilt angle of $\sim 2.3^\circ$ relative to the propagating directions of the pump and coupling lasers.

Figure 2(a) shows the generation of the photon pair along the cascade decay paths corresponding to the $6S_{1/2}(F=4) - 6P_{3/2}(F'=3, 4, 5) - 8S_{1/2}(F''=4)$ transition of the ^{133}Cs atom. The wavelengths of the pump and coupling lasers were 852 nm for the $6S_{1/2} - 6P_{3/2}$ transition and 795 nm for the $6P_{3/2} - 8S_{1/2}$ transition. The natural linewidths of the $6P_{3/2}$ and $8S_{1/2}$ states are 5.2 MHz and 1.7 MHz, respectively

[33]. To prevent uncorrelated photons due to single-photon resonance, their optical frequencies were detuned beyond the Doppler broadening of the warm Cs ensemble.

The photon pair generated via the SFWM process in a cascade-type atomic system is strongly correlated with two-photon coherence because of the possibility of nonlinear optical process enhancement via two-photon coherence [23]. In our experiment, we selected the $6S_{1/2}(F = 4) - 8S_{1/2}(F'' = 4)$ transition for fulfilling the Doppler-free two-photon resonant condition for photon-pair generation. Therefore, we note here that the two-photon resonance between the $6S_{1/2}(F = 4) - 8S_{1/2}(F'' = 4)$ transition should be maintained for the stable operation of the photon pair generated from the chip-scale Cs cell.

We first investigated the two-photon absorption (TPA) spectrum in the chip-scale Cs vapor cell. Figure 2(b) shows the transmittance spectrum (blue curve) for the $6S_{1/2}(F = 4) - 6P_{3/2}(F' = 3, 4, 5) - 8S_{1/2}(F'' = 3, 4)$ transition as a function of the detuning frequency of the pumping laser, where the optical frequency of the coupling laser is detuned to ~ 1.35 GHz from the $6P_{3/2}(F' = 5) - 8S_{1/2}(F'' = 4)$ transition. The gray-colored curve denotes the saturated absorption spectrum (SAS) of the pump laser for the $6S_{1/2}(F = 4) - 6P_{3/2}(F' = 3, 4, 5)$ transition. From the figure, we can observe the two TPA signals of the $F'' = 3$ and 4 states of the $8S_{1/2}$ hyperfine states beyond the Doppler broadening of the Cs ensemble.

When the optical frequency of the pumping laser is scanned around the TPA spectrum, the TPA spectrum is clearly observed in the chip-scale Cs vapor cell, as shown in Fig. 2(c). The TPA signal of the $F'' = 3$ state is larger than that of $F'' = 4$ because the detuning frequency of the $F'' = 3$ state is smaller than that of $F'' = 4$, corresponding to a frequency difference of ~ 877 MHz between the $F'' = 3$ and 4 hyperfine states.

The TPA spectral width was measured to be $\sim 28(3)$ MHz. Here, we note that the TPA spectral width is related to the two-photon coherence length of photon pairs from Doppler-broadened atomic ensembles [23]. However, the measured TPA spectral width is greater than the natural linewidth (1.7 MHz) of the $8S_{1/2}$ state because of two-photon Doppler broadening due to the wavelength difference between the pump and coupling lasers. In our experiment, the two-photon Doppler shift (ω_{mo}) for the 795 nm coupling laser and the 852 nm pump laser in the warm Cs vapor cell can be expressed as $\omega_{mo} = (\vec{k}_p - \vec{k}_c) \cdot \vec{v}$, where $\vec{k}_p$ and $\vec{k}_c$ are the wave vectors of the pump and coupling lasers, respectively, and $\vec{v}$ is the atom velocity. The value of ω_{mo} was estimated to be ~ 21 MHz at a velocity of 250 m/s. Additional causes of spectral broadening such as laser linewidth and transit broadening of the focused beam also need to be considered. The transit time broadening is estimated to be ~ 2.8 MHz with the beam waist of ~ 60 μm inside the cell.

Experimental Results

We investigated the properties of the temporal correlated photon pairs emitted from the chip-scale atomic vapor cell. Figure 3(a) shows the temporal biphoton waveform of the photon pair from the chip-scale ^{133}Cs vapor cell, i.e., the normalized cross-correlation function $g_{\text{SI}}^{(2)}(\tau)$ between the signal and idler photons, where τ denotes the time delay between the signal and idler photons. To obtain the $g_{\text{SI}}^{(2)}(\tau)$, we measured the coincident detection histogram of the signal and idler photons as a function of τ using a time-correlated single-photon counter (TCSPC) in the start-stop mode with a 88-ps time resolution, and then normalized the measured coincidence histogram to the accidental coincidence count. The $g_{\text{SI}}^{(2)}(\tau)$ spectrum exhibits a full-width at half-maximum (FWHM) of $\sim 4.9(5)$ ns, which is related to the coherence time of the signal and idler photons. However, the measured FWHM of $g_{\text{SI}}^{(2)}(\tau)$ is estimated to be approximately two times greater than the inverse of the Doppler-broadening linewidth of the warm ^{133}Cs atoms. The main cause of the broadened FWHM of $g_{\text{SI}}^{(2)}(\tau)$ is the two-photon Doppler shift due to the wavelength difference

between the counter-propagating pump and coupling lasers. The atomic velocity groups beyond the two-photon resonance do not contribute to the collective two-photon coherence for photon-pair generation from our chip-scale Cs vapor cell. Therefore, the spectral width of the coherently superposed photons is narrower than the Doppler broadening of the warm Cs ensemble.

The maximum value of $g_{\text{SI}}^{(2)}(\tau)$ was measured to be 622(8), and the Cauchy–Schwarz inequality was estimated to be a factor of $\sim 100,000$, which clearly indicates the quantum nature of the paired photons [34]. The large value of the Cauchy–Schwarz inequality indicates that the SFWM photon-pair flux was enhanced and the uncorrelated single-emission fluorescence from the chip-scale atomic vapor cell was suppressed.

From Fig. 3(a), we can observe the quantum beats in the temporal biphoton waveform. Here, we note that quantum beats have also been reported in cascade decay systems of atomic vapors [35–37] and cold atoms [38–39]. The quantum beats are understood as the interference of the signal and idler photon pairs generated via the three decay paths corresponding to the hyperfine states of the $6\text{P}_{3/2}$ intermediate level in the $6\text{S}_{1/2}(F=4) \rightarrow 8\text{S}_{1/2}(F''=4)$ transition, as shown in Fig. 3(b). These three decay paths cannot be distinguished by the SPDs. The beating period corresponds to the hyperfine splitting with frequency differences of 251 MHz ($F''=4$ and 5) and 201 MHz ($F''=3$ and 4) of the $6\text{P}_{3/2}$ state.

We investigated the heralding efficiency according to the OD. In our experiment, the temperature of the vapor cell was optimized for the heralding efficiency. Figure 4 shows the heralding efficiency (red squares) as a function of OD under the conditions on the pump power of 0.5 mW and the coupling power of 5 mW. The decrease in the heralding efficiency at high OD can be explained by reabsorption of the idler photon in the medium, whereas the optimal OD for high heralding efficiency is explained by the enhancement in the collective emission into the phase-matched direction [40–41].

In our photon-pair source from the chip-scale ^{133}Cs vapor cell, the photon-count rate, photon-pair coincident count rate, and value of $g_{st}^{(2)}(\tau)$ can be changed by varying the pump and coupling powers as well as the atomic density of the atomic vapor cell. In particular, the photon-pair coincident count rate is an important factor that determines the properties of the photon-pair source from the chip-scale atomic vapor cell.

Figure 5(a) shows the signal (blue squares) and idler (red circles) single-count rates as functions of the pump power for a coupling power of 5 mW. The coincidence count rate and the maximum value of $g_{st}^{(2)}(\tau)$ are shown in Fig. 5(b) for the coincidence window of 8.8 ns. The counting rates of the signal and idler photons were measured to be 795 kHz and 446 kHz, respectively, and the coincidence counting rate of the photon pair was obtained to be ~20 kHz with 0.8 mW of pump power. From the experimental results, the heralding efficiency for idler photons was calculated as 4.5(1)%, for which the fiber coupling efficiency, detection efficiency, and reflection losses of chip-scale cell windows were not considered.

We note here that in our experiment, the $6S_{1/2}(F=4)-8S_{1/2}(F^2=4)$ transition for the generation of photon pairs is not a two-photon cycling transition, which is used to treat the three-level atomic system such as the $5S_{1/2}(F=2)-5P_{3/2}(F^2=3)-5D_{5/2}(F^2=4)$ transition of ^{87}Rb [21]. Therefore, the generation rate of the photon pair may decrease when compared with that for the two-photon cycling transition, because the SFWM process can be significantly enhanced in an atomic medium with pure two-photon coherence in a simple three-level atomic system. Furthermore, in our study, the SPD detection efficiency of the idler photon (852 nm) was ~9% lower than that of the signal photon (795 nm). Nevertheless, our results confirm that our photon-pair source based on the chip-scale Cs vapor cell is comparable with previous realized sources based on the ordinary atomic vapor cell [23-24].

Conclusion

In conclusion, we experimentally demonstrated a photon-pair source realized using a microfabricated chip-scale Cs vapor cell. Bright photon pairs could be generated from the chip-scale atomic ensemble with an interaction length of 1 mm. From the cross-correlation between the signal and idler photons, we found that the Cauchy–Schwarz inequality was violated by a factor of 10^5 . We confirmed that the SFWM photon-pair flux was enhanced, and the photon pair from the chip-scale atomic vapor cell was strongly temporally correlated. The characteristics of the photon-pair source realized using the chip-scale Cs vapor cell were comparable with those realized from ordinary atomic vapor cells. Furthermore, we observed the quantum beats of the temporal biphoton waveform of the photon pair due to the multiple channels of the SFWM process relating to the hyperfine states of the intermediate $6P_{3/2}$ state. We believe that our approach can be potentially used in future chip-scale atomic quantum devices such as integrated photonic systems and other related devices. Such devices may enable the construction of practical scalable quantum networks based on atom–photon interactions.

Declarations

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Author Contributions

H.S.M. conceived the project. H.K., J.P., H.-G.H., T.Y.K., J.P., and H.S.M. designed the experimental setup and performed the experiments. H.K., J.P., and H.S.M. discussed the results and contributed to the writing of the manuscript.

Additional Information

Competing Interests: The authors declare no competing interests.

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Figures

Figure 1

Experimental setup for the generation of photon pairs from a chip-scale Cs atomic cell. (a) Photograph of the chip-scale Cs atomic cell. (b) Structure of the fabricated chip-scale Cs atomic cell (Cs dispenser, channel, and photon-pair chamber). (c) Schematic of the experimental setup for photon-pair generation via spontaneous four-wave mixing (SFWM) (lens focal length = 300 mm).

Figure 2

Experimental configuration for the generation of photon pairs from Cs atomic ensemble. (a) Cascade emission of signal and idler photons via spontaneous four-wave mixing (SFWM) in the $6S_{1/2}$ – $6P_{3/2}$ – $8S_{1/2}$ transition of ^{133}Cs atom. (b) Transmittance spectrum (blue curve) in the chip-scale atomic vapor cell and saturated absorption spectrum (gray curve) in an ordinary atomic vapor cell of pump laser. (c) Two-photon absorption (TPA) spectrum of the $6S_{1/2}(F=4)$ – $6P_{3/2}(F'=3, 4, 5)$ – $8S_{1/2}(F''=3, 4)$ transition.

Figure 3

Temporal biphoton waveform. (a) Normalized cross-correlation function, $g_{si}^{(2)}$, between signal and idler photons (blue curve). (b) Quantum beats between the three channels of the SFWM process relating to the $F' = 3, 4$, and 5 states of $6P_{3/2}$ states in the $6S_{1/2}(F = 4) - 8S_{1/2}(F'' = 4)$ transition.

Figure 4

Signal photon heralding efficiency. Herald efficiency (red squares) as a function of OD in the OD range from 1 to 10.

Figure 5

Count rates of photon pair. (a) Single-count rates for signal and idler photons. (b) Maximum value of normalized temporal cross-correlation function and coincidence count rate of photon pairs as functions of pump power for coupling power of 5 mW.